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Stanley R. Mohler

Federal Aviation Administration
Washington, D. C.

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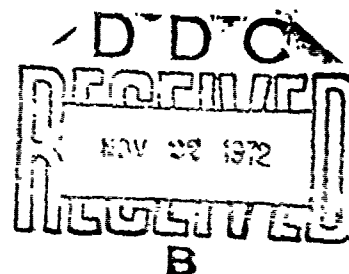
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16. Abstract <p>Sport, precision, and competitive aerobatics, and especially air show and demonstration flying are enjoying a rebirth of interest exceeding that of the 1930's. Improved aerobatic airplanes and power plants are in the hands of more civilian pilots than ever before. These aircraft enable the pilot to easily initiate maneuvers which exceed human tolerances, yet not overstress the aircraft. Military aircraft reached this point in World War II and the G-suit was perfected to protect the pilot. The military groups still use the G-suit but this equipment is impractical for most civil aerobatic activities. This paper provides information on (1) the nature of aerobatic G forces, (2) human physiology in relation to G forces, (3) human tolerances to various levels and times of exposure to G forces, and (4) means by which tolerance to G forces may be increased in terms of (a) the general physical condition and (b) the time during the maneuver when the G forces are imposed.</p>			
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G EFFECTS ON THE PILOT DURING AEROBATICS

Many prospective aerobatic trainees enthusiastically enter aerobatic instruction, but find their first experiences with G forces to be unanticipated and very uncomfortable. The uninformed student may actually lose consciousness at three (+) G's and incorrectly assume that he is unfit for aerobatics. If the aerobatic instructor does not have a basic understanding of the physiology of G force adaptation, he will be unable to clearly explain the phenomenon, and the student will likely be lost to further aerobatic activity.

No airplane pilot is "complete" without training in stalls, which is why proficiency in stall recovery must be demonstrated prior to solo. Similarly, unless the pilot has instrument training and an instrument rating, he is limited to fair weather operations and is a potential hazard should he get into loss-of-outside-reference conditions in haze, fog, rain or darkness. This is why all airline transport pilot certificate applicants must demonstrate instrument proficiency. Likewise, the complete pilot is proficient in spin recovery, and demonstration of this capability is required for the instructor certificate. Many feel that the complete pilot also must have some aerobatic training, especially today when wake turbulence upsets are potentially more severe than in past years because of the introduction of large jet aircraft.

Push-over Forces

Let us assume that an aircraft is flying along a straight course with wings level and that the pilot pushes over into a 70° dive (Figure 1). The force (f) necessary to deflect the aircraft from its prior straight path through the curved path is directly proportional to the product of the mass (m) of the aircraft and the rate of change of velocity (a for acceleration) experi-

enced. In physics this is stated by the formula $f=ma$.*

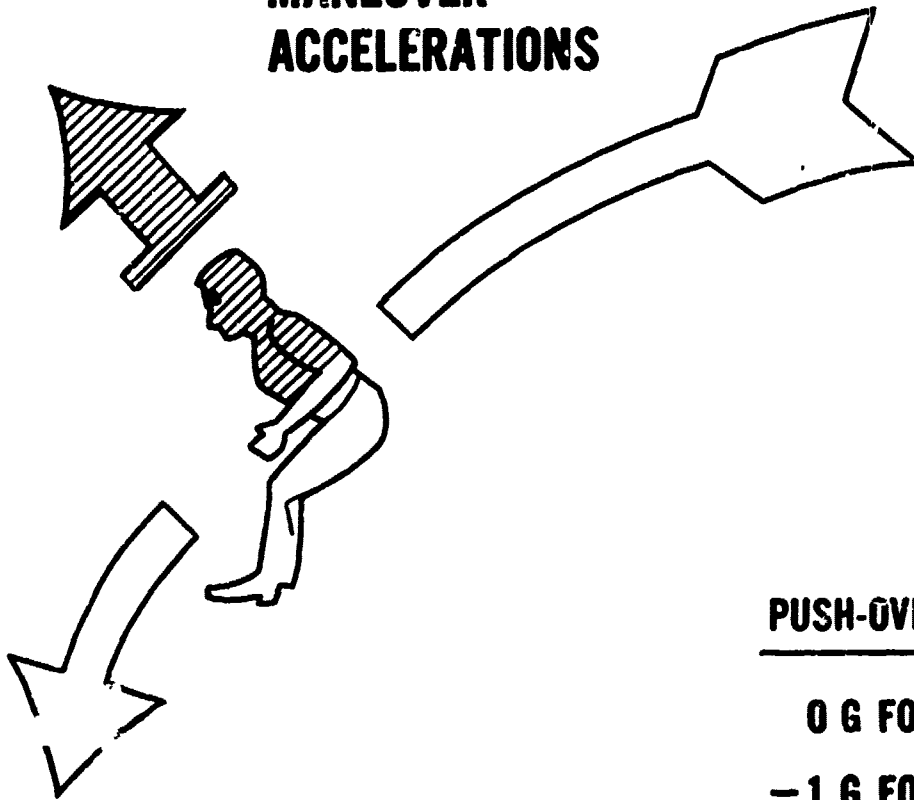
We define one (+) G as the strength of the gravitational force (which tends to accelerate a mass toward the center of the earth) all of us experience when stationary at or near the surface of the earth (note that a body is not accelerating when it is standing still or is moving at constant velocity in a straight line—if it makes a curve, even at constant velocity it accelerates because it moves away from the straight path). This force may be expressed in terms of an individual's "weight".

If an elevator begins to move up while one is standing in it, one experiences a "heaviness" feeling during the acceleration phase. If the upward acceleration is great enough to double one's weight should he be standing on scales at this time, we define the accelerative force as two (+) G's. When the elevator reaches constant velocity as it moves up, the acceleration returns to zero and the individual is back at one (+) G. As the elevator begins to decelerate as it moves toward the top of the building (if not, it might shoot through the roof), the individual, not strapped to floor, tends to continue going up and, the scales show less than the individual's weight (if the weight shown is half that at one (+) G, convention refers to this as an accelerative force of 0.5 (+) G.) If the elevator

*Acceleration (a) is the time-rate of change of velocity. It is a vector quantity, i.e., it has direction and magnitude. With a constant velocity, one can have acceleration due to a change in the direction of motion of a moving mass. The case of a uniform change in the magnitude only of velocity (as in the case of a freely falling body) is called uniformly accelerated linear motion. When the direction only is changed this is called uniform curvilinear motion or translatory motion in a circle.

Acceleration is equal to V^2 over R and is directed toward the center of the circle. R is the radius of the circle. If the path of the airplane or object does not follow a perfectly circular route, the motion is not uniform curvilinear motion.

AIRCRAFT MANEUVER ACCELERATIONS



PUSH-OVER TO 70° DIVE

0 G FOR 35 SECONDS

-1 G FOR 15 SECONDS

FIGURE 1.—Negative G's in a "pushover".

rapidly reversed course and began accelerating downward so that the individual and the elevator fell solely by the accelerative pull of gravity, the individual would experience during this period zero G (since his body would register zero on the scales). If the elevator were forced to accelerate downward faster than the acceleration caused by the pull of gravity alone, and if the individual were tied to the elevator, so that he would be pulled with it, he could experience "negative" G's. If a spring scale were placed between the individual and the floor, the footward tug in pounds on his body could be measured, and if this tug were to be exactly equal to his weight, we would call this an acceleration of one (-) G.

Figure 1 illustrates that a pushover from straight, wings level, flight to a 70° dive, can produce forces on the aircraft (and the strapped-

in pilot) of 0 G for 35 seconds to one (-) G for 15 seconds (depending upon how hard the pilot pushes over).¹³ Other G/time combinations are also possible, of course. If the pilot were not snugly strapped in, the one (-) G acceleration would result in his departing the aircraft at a tangent to its curved flight path, and, through a "parabolic arch" free-fall, reach a terminal velocity at one (+) G (not counting the effect of wind blast, which, depending upon the pilot's speed at exit exerts a certain drag force.) At the zero G acceleration, the aircraft and the pilot are both falling solely by the pull of gravity and the pilot has the sensation of floating. Note that at one (-) G, the blood and body organs, especially the heart, the liver, and the intestines, tend to move toward the head of the pilot (more about this, later).

AIRCRAFT MANEUVER ACCELERATIONS

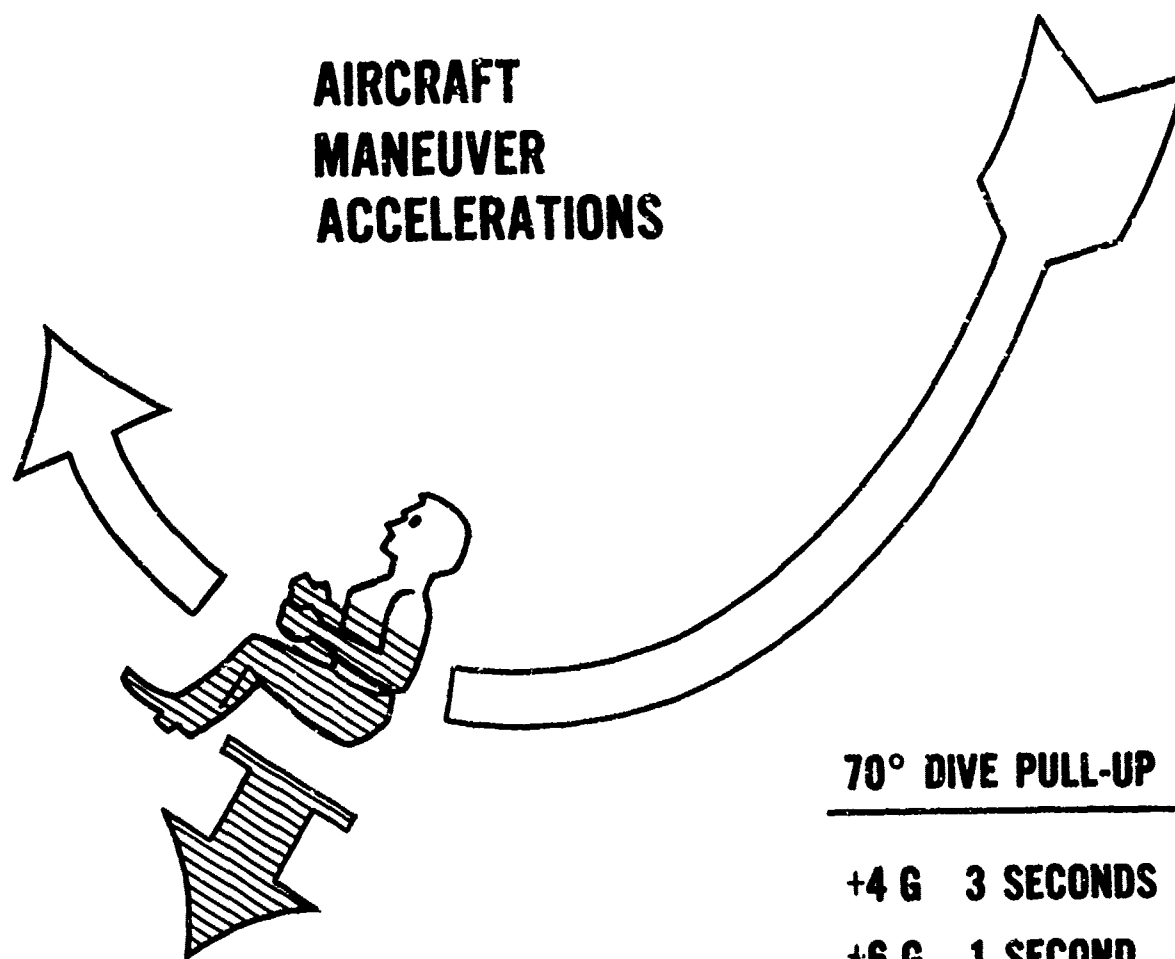


FIGURE 2.—Positive G's in a "pull-up".

Pull-up forces

Figure 2 reveals possible force in a 70° dive and pull-up. These are four (+) G for three seconds to six (+) G for one second. Note how the blood and body organs tend to pool toward the lower part of the body. Obviously, since the human brain requires essentially continuous blood circulation from the beats of the muscular pump, the heart, for maintenance of an adequate oxygen supply, and since the circulatory system is a complex network of flexible vessels of which the major vessels run lengthwise in the body, there is a physiological limit to the time the pilot can withstand these higher G forces before losing consciousness. A brief loss of consciousness in a maneuver can lead to improper control movement causing structural failure of the aircraft or collision with another object or terrain.

Steep turn forces

In steep (+) G turns, the centrifugal force tends to push the pilot through the floor boards, and as shown in Figure 3, a steep turn of 180° change of direction will yield two (+) G for 35 seconds and if made in 15 seconds can yield five (+) G. Every private pilot has been taught that (by reason of geometry and vector forces) all 60° banked turns held at a constant altitude pull two (+) G during the turn.⁷ * The difference in this maneuver between fast and slow aircraft is that the faster aircraft covers more area during the maneuver.* The same interrelationships

* Assuming constant acceleration, if one doubles the velocity of an airplane in a 60° banked turn, the radius of curvature becomes four times greater. If one were to triple the velocity, nine times greater. For a constant acceleration the radius of curvature varies as the square of the velocity. The same applies, of course, to the diameter of a loop. High speed loops take a great deal of vertical airspace.

AIRCRAFT MANEUVER ACCELERATIONS

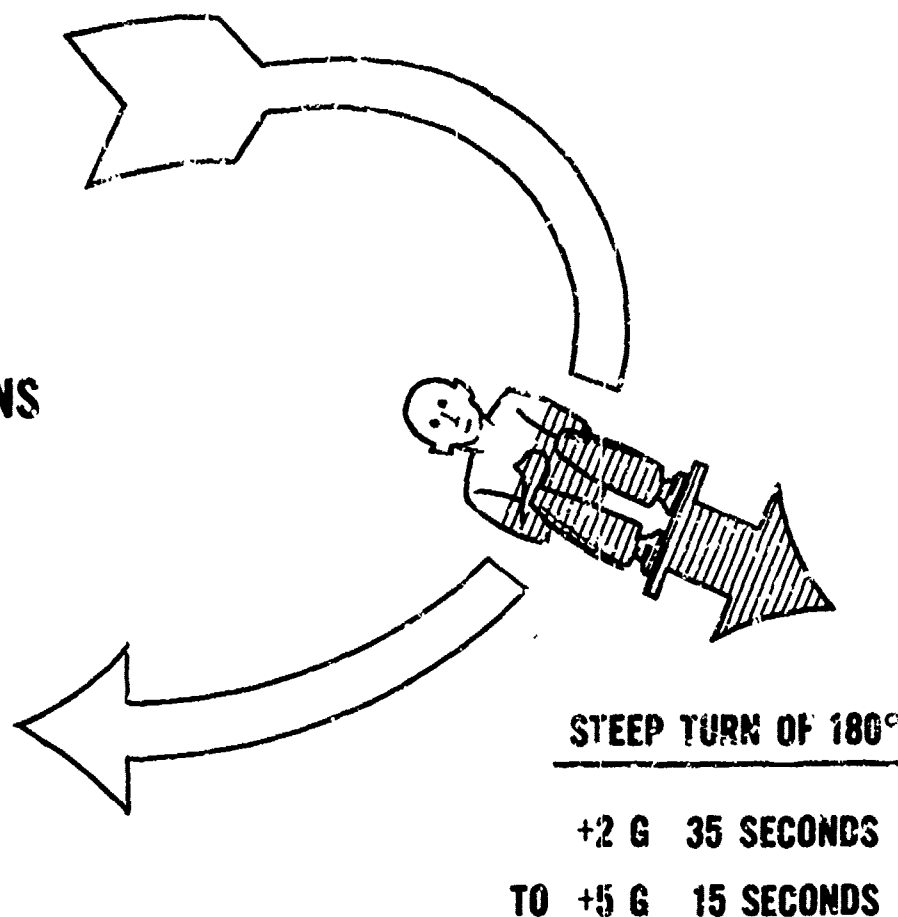


FIGURE 3.—Positive G's in steep turns of 180° direction change.

exist in all aerobatic maneuvers, with aircraft capabilities varying according to design and power plant characteristics.**

Aircraft G limits

Most aerobatic maneuvers for demonstration are variations of the loop, slow roll and snap*

** When an airplane is banked 60° with coordinated controls (left stick, left rudder) and kept at a constant flight attitude, the airplane describes a circular path to the left. The resultant vector from the center of lift of the aircraft is perpendicular to the lateral and longitudinal axes of the aircraft and is twice as long as the lift vector from the same point. The result is that a 30°/60°/90° triangle exists, having a hypotenuse of two and an opposite side (with respect to the 30° angle) of one. The sine of 30° is 1/2. Therefore, the force acting on the pilot "through the floorboards" in a 60° banked constant altitude turn is twice that in straight and level flight. For further details see Kershner's and Hurt's publications.

If the maneuver is accomplished to impose a (+) G load, it is referred to as an "inside" maneuver, while (-) G load maneuvers are termed "outside".

The FAA has established G load design limit factors for civil certified aircraft which weigh under 12,500 pounds and these are as follows (each limit is supplemented by a times "1.5" safety factor in case of occasional accidental excess loading):

Category	+ G	- G
Normal	3.8	0.4 times 3.8
Utility	4.4	0.4 times 4.4
Aerobatic	6.0	0.5 times 6.0

The above limits are minimum design requirements under Federal Aviation Regulations 23.337 (see Code of Federal Regulations, Title 14, Aeronautics and Space, FAR Part 23, 1972).

Terminology for Plus and Negative Accelerations on the Pilot

In the same fashion as with aircraft design limits for G, the human body has upper limits, as modified by the necessity to keep the physiologic functions operational. In order that a clear definition of the human limits to G can be presented, certain arbitrarily established parameters must be utilized. Figure 4 provides a standardized terminology for describing G forces acting on the body of a pilot during aerobatic maneuvers.¹ It will be noted that since the top of the heart elastically hangs in the chest from the aorta and certain nearby tissue sheets the direction in which the heart moves relative to the skeleton when the whole body is

accelerated, determines the name given to the force. For example, an inside loop pulls (+) G's and tends to move the heart toward the pelvis, and since the long axis of the spine is referred to as the G_z axis, this maneuver is said to pull (+) G's in the Z axis, and, if 2 G's were pulled at a point, this would be written: 2 (+) G_z . An outside loop pulling one (-) G's at a point would be indicated by 1 (-) G at that point.

The G_y axis runs through the shoulders and has some applications in snaps and spins (but requires a specially mounted G meter for measurement). The G_x axis runs through the chest and has a certain bearing on tail slide maneuvers and recoveries and crash impacts, where seat belts and shoulder harness prevent excess move-

TERMINOLOGY FOR ACCELERATION FORCES ON THE BODY

VECTOR DIRECTION NAMED FOR THE DIRECTION THE HEART MOVES RELATIVE TO THE SKELETON UNDER THE IMPOSED ACCELERATION

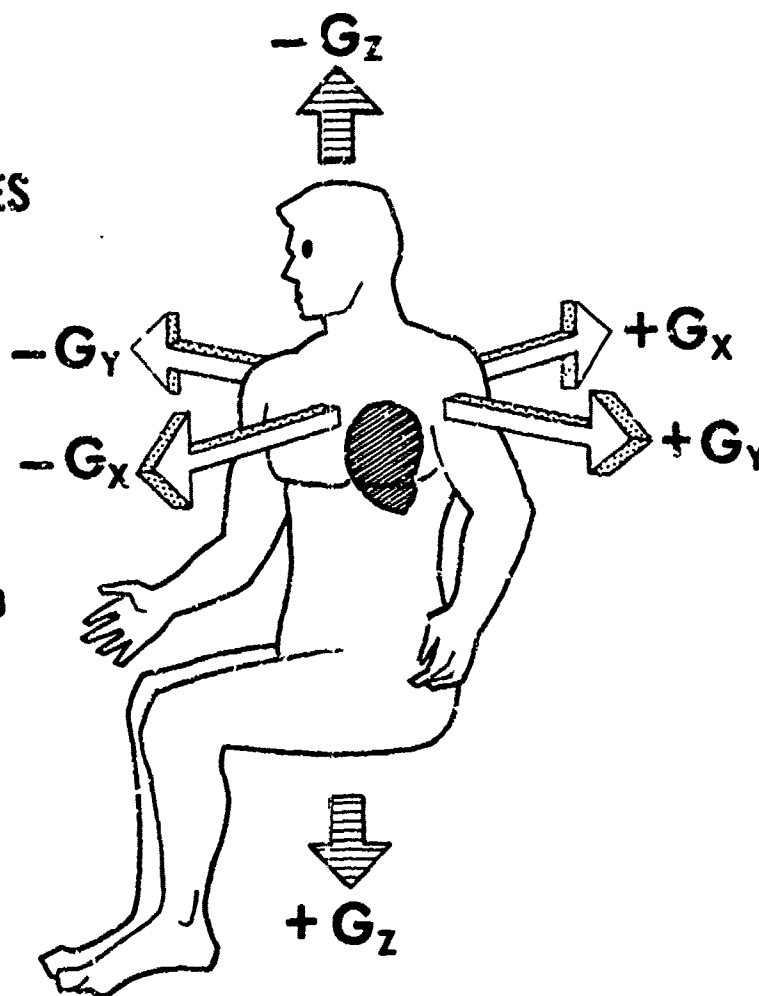


FIGURE 4.—Standardized acceleration terminology.

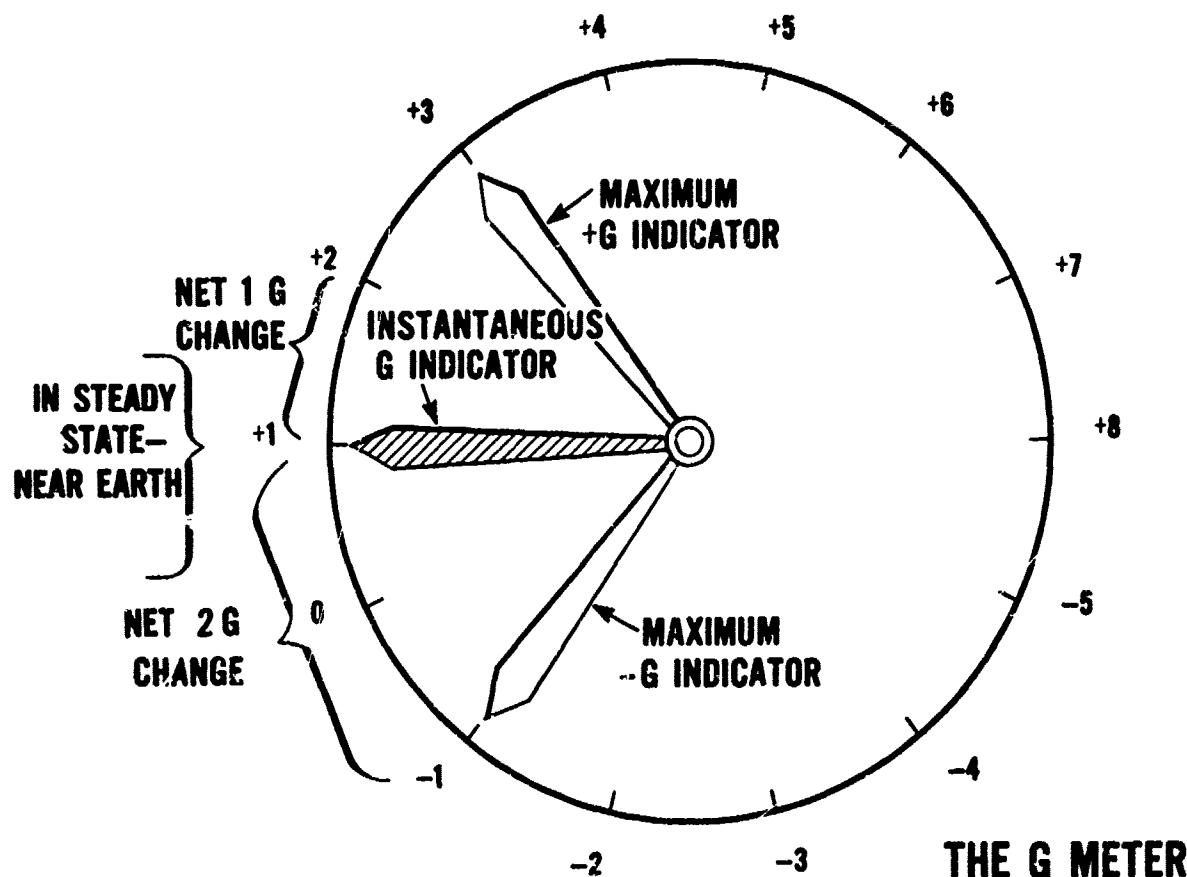


FIGURE 5.—The accelerometer or "G" meter.

ment toward the $(-)$ G_x direction with sudden decelerations. Physiologically, because of its design, features the body can adapt much more readily during aerobatic flight to G_x and G_y axis accelerations than is so with the G_z axis, hence, we will direct our major attention here to the G_z axis accelerations $(+)$ and $(-)$.

The G Meter

Figure 5 portrays the instrument panel G meter which indicates the accelerative forces experienced by the aircraft which, by virtue of the pilot's cockpit seating arrangement, are exerted through the G_z axis of the pilot.

Note that one needle stays at the maximum $(+)$ G's experienced during a maneuver, one needle stays at the maximum $(-)$ G's, and one fluctuates continuously with the imposed acceleration force (in straight and level horizontal flight this will read one $(+)$ G.) An instant reset button is present allowing then centering to one

$(+)$ G of all three needles prior to the next maneuver.

Note also that the pilot experiences a net change of one G during a maneuver from a one $(+)$ G baseline that pulls two $(+)$ G, while he experiences a net change of two G's during an outside maneuver starting from a one $(+)$ G baseline and going to a one $(-)$ G level.

If the pilot performs a maneuver from a one $(+)$ G baseline to 4 $(+)$ G's, his net change is 3 G's, while if he performs from the same baseline a 4 $(-)$ G maneuver, his net change is 5 G's. Negative maneuvers of the same numerical value as positive maneuvers but with opposite sign, impose greater physiological net changes, therefore, on the pilot. In addition, as discussed later, the body's physiologic adaptive mechanisms to combat G load effects in the G_z axis is designed primarily to adapt to $(+)$ G_z changes (since we evolved in a $(+)$ G_z environment) and function poorly against $(-)$ G_z accelerations.

Maneuvers

Typical aerobatic maneuvers were filmed by the author using an on-board movie camera and were also timed by a stop watch. Light aerobatic aircraft of the Beech Musketeer Aerobatic Sport III and the Beech T-34 type were used. In addition, the G forces experienced were recorded at critical points in the maneuvers. The data would be modified somewhat by other types of aircraft and by varying the force of control application.⁴ Appreciation is extended to Mr. William Kershner who assisted with most of the maneuvers.

Figure 6 reveals that the inside loop in the above type aircraft takes about 15 seconds and pulls 3.5 (+) G for 1 second at the 4-5 o'clock position and at the 7-8 o'clock position. The

rest of the loop averages about 1 (+) G. The build-up to, and drop-off from, 3.5 (+) G is necessary to change the direction of the relatively fast aircraft as it enters the six o'clock position ($f=ma$) to an upward direction, and the pilot's pull back on the stick is, accordingly, of correspondingly greater force at the 3.5 points. The pull-out entails the 3.5 (+) G level because the accelerating aircraft must be changed in direction from straight down to the horizontal against the pull of gravity.

The average "naive" person or novice aerobatic student will "gray out" (loss of vision due to decreased blood flow through the brain and retina) at 3.5 (+) G's, especially if the individual doesn't expect the imposition of the accelerative force and is unprepared or does not know how to adapt. Accordingly, this simple maneuver

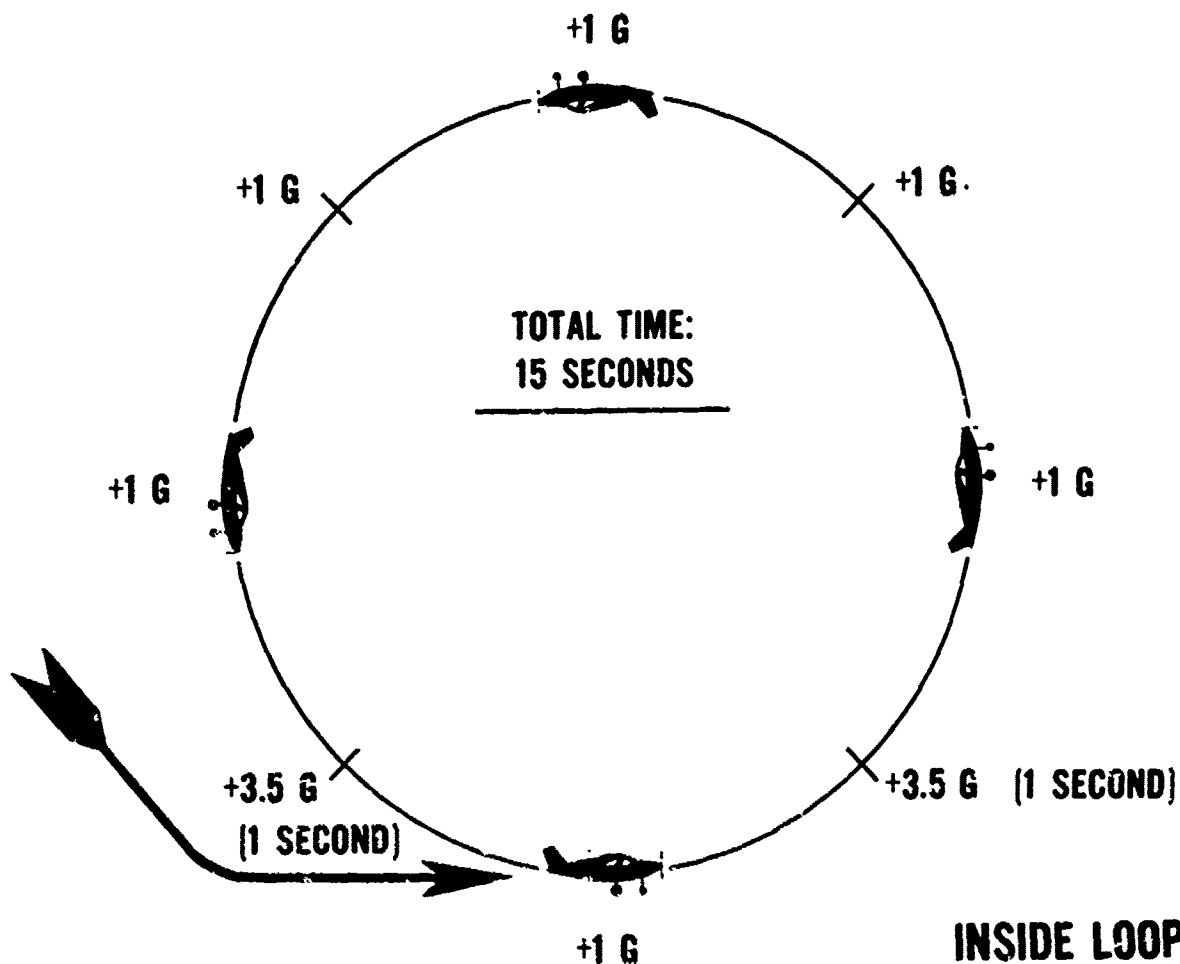


FIGURE 6.—The forces and times in a loop. In a Beech Musketeer Aerobatic Sport III, the entry is at 140 mph to get one G at the top at 70 mph.

can frighten the initiate if some explanation and guidance is not given by the instructor or demonstrator ahead of time. The experienced pilot in good health knows how to adapt and what to expect, and at the levels of G shown for the times given in Figure 6, derives pleasure from the physiological and optical sensations. The chances are he wants more. Years ago, for example, pilots vied with one another for the maximum number of consecutive inside loops. Charles "Speed" Holman made 1,453 consecutive loops in 1928 at St. Paul, Minnesota, taking five hours (this gives an average time of a little over 12 seconds per loop).²

It is noted also that, initially, persons may become airsick during aerobatics because of the unusual stimulations of the inner ear plus the anxiety of not knowing exactly what is happening. This tendency is usually rapidly lost (apparently through "habituation" of the semicir-

cular canals) and for most persons never becomes a serious problem again.

The inside aileron roll is a maneuver between the slow-roll (which pulls zero to one (-) G) and the barrel roll (which is sort of a spiral loop and pulls plus G's all the way around). The aileron roll (see Figure 7) takes six seconds for completion, either to the left or the right and reaches a maximum of 2.5 (+) G's.

The inside snap (Figure 8) takes three seconds to the left and pulls 2.5 (+) G's. Since the snap to the right in aircraft having propellers which rotate clockwise (when seen from the rear of the aircraft) is entered at a slightly higher air-speed, the snap takes 2.9 seconds and recovery pulls three (+) G's. The propeller spiral slip stream tends to yaw the aircraft to the left, hence, the slightly higher entry speed in right snaps to compensate for this effect. This maneuver is so rapid that it is over before the novice realizes

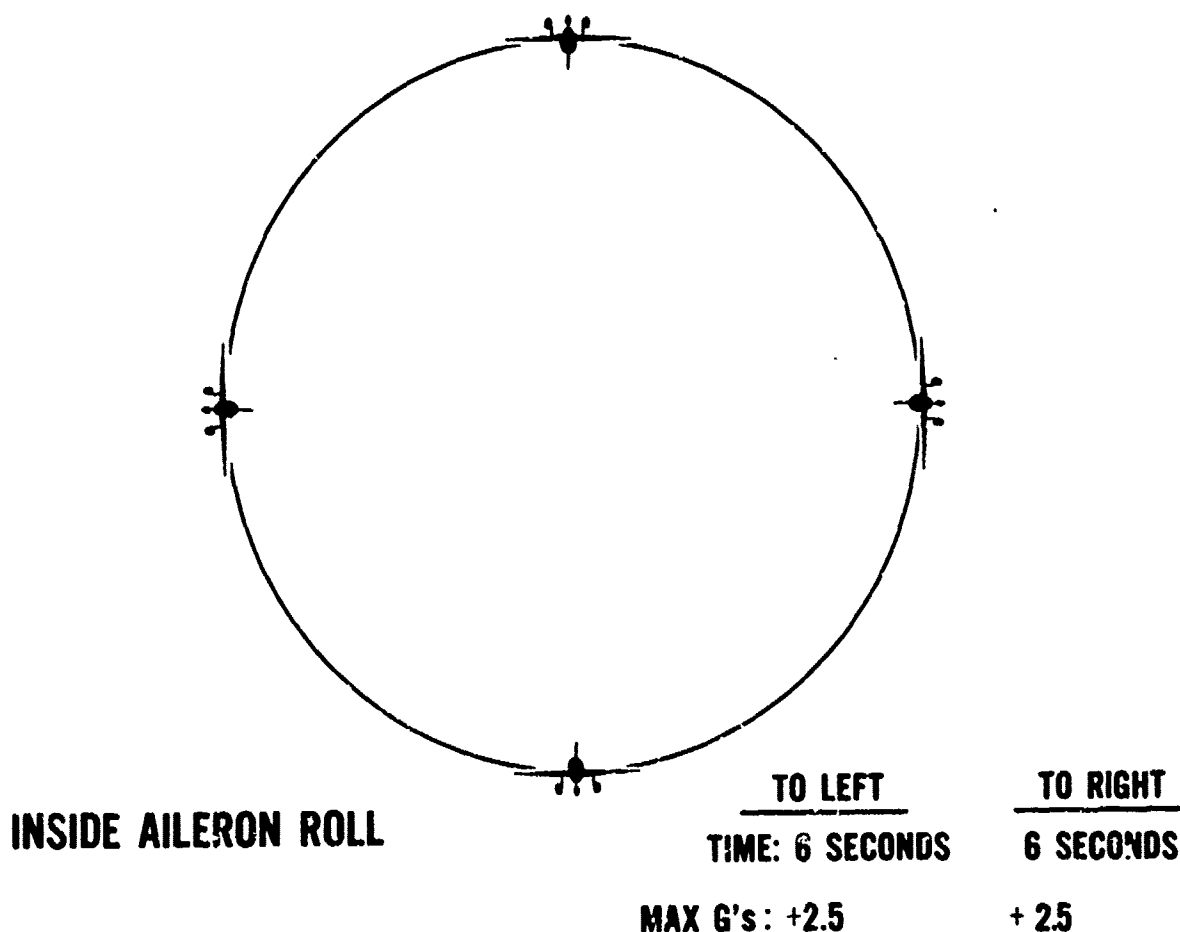
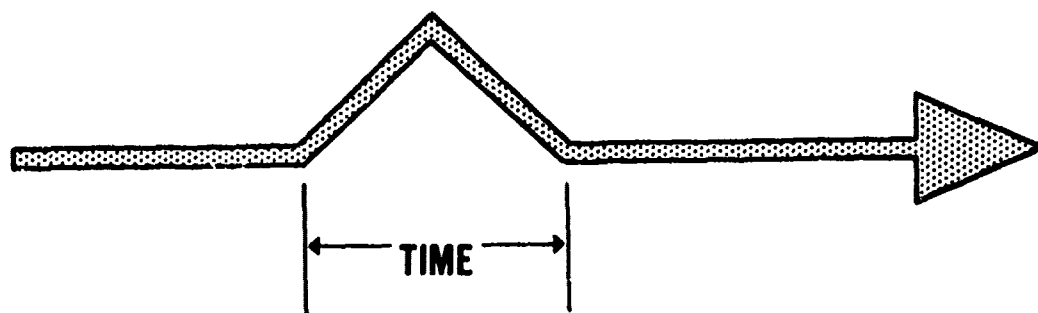


FIGURE 7.—The aileron roll is perhaps the best maneuver to use to introduce novices to aerobatics.



INSIDE SNAP ROLL

	TO LEFT	TO RIGHT
TIME:	3 SECONDS	2.9 SECONDS
MAX. G's:	+2.5	+3

FIGURE 8.—The snap roll is the fastest roll maneuver.

what happened. He may be confused and claim that a left snap was actually to the right.

Three turn spins (Figure 9) require a loss of altitude of about 1,100 feet in the aircraft referenced, taking 12 seconds, and leading to 3.5 (+) G's on pull-out for three seconds. Some aircraft pitch partially upside down, nose low, on entry, a frightening experience to some novices, and the increasingly rapid roll rate in certain aircraft plus the nose low attitude is also frightening if not understood. Subtracting three seconds for recovery, one can see that each spin turn is three seconds, approximately that of one snap (the snap is, in effect, a horizontal spin, entered from an accelerated stall at a speed somewhat higher than that of spin entry).

Figure 10 shows the inside square loop which takes 24 seconds and contains four 4-second legs and four 2-second vertical ninety degree turns. Note that the abrupt change of attitude from level to nose-up and nose-down to level pull 4.2 (+) G's for as high a speed safely attainable by the aircraft ($f=ma$). This level of G's will definitely black out the unprepared person. For this short period of time, the body of a 170-pound pilot weighs 714 pounds. The arms and

head are four times as heavy and the novice feels very uncomfortable. A portion of the top of the square loop records zero G's in aircraft without inverted fuel flow capability and an oil system suitable for inverted flight, since the aircraft actually follows a somewhat parabolic falling maneuver as the engine cannot sustain negative G's for more than a few seconds. In aircraft with systems suitable for inverted flight, one (-) G would be recorded across most of the top of the square loop.

Physiologic Adaptation to G Forces

Figure 11 illustrates the arterial blood flow pattern as the blood leaves the heart. The heart pumps the oxygenated blood upward through the body's largest artery, the aorta. The aorta arches 180° and sends a column of blood downward to the trunk and lower limbs. The carotid arteries exit from the arch of the aorta and serve the head, including the brain and eyes. The subclavian arteries also receive blood from the aorta and serve the arms.

When the mean blood pressure rises above a certain "normal" level in the aorta and carotid arteries, the diameter of these elastic vessels in-

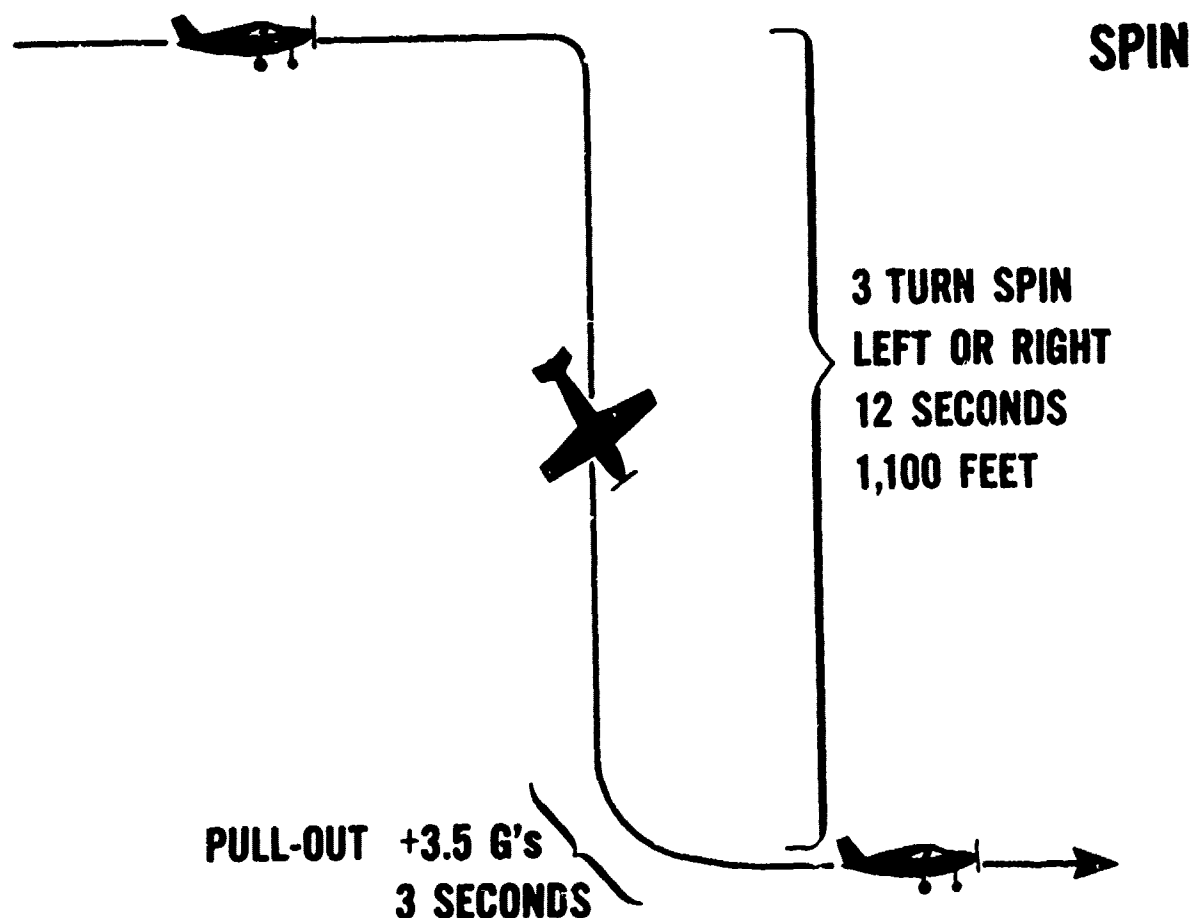
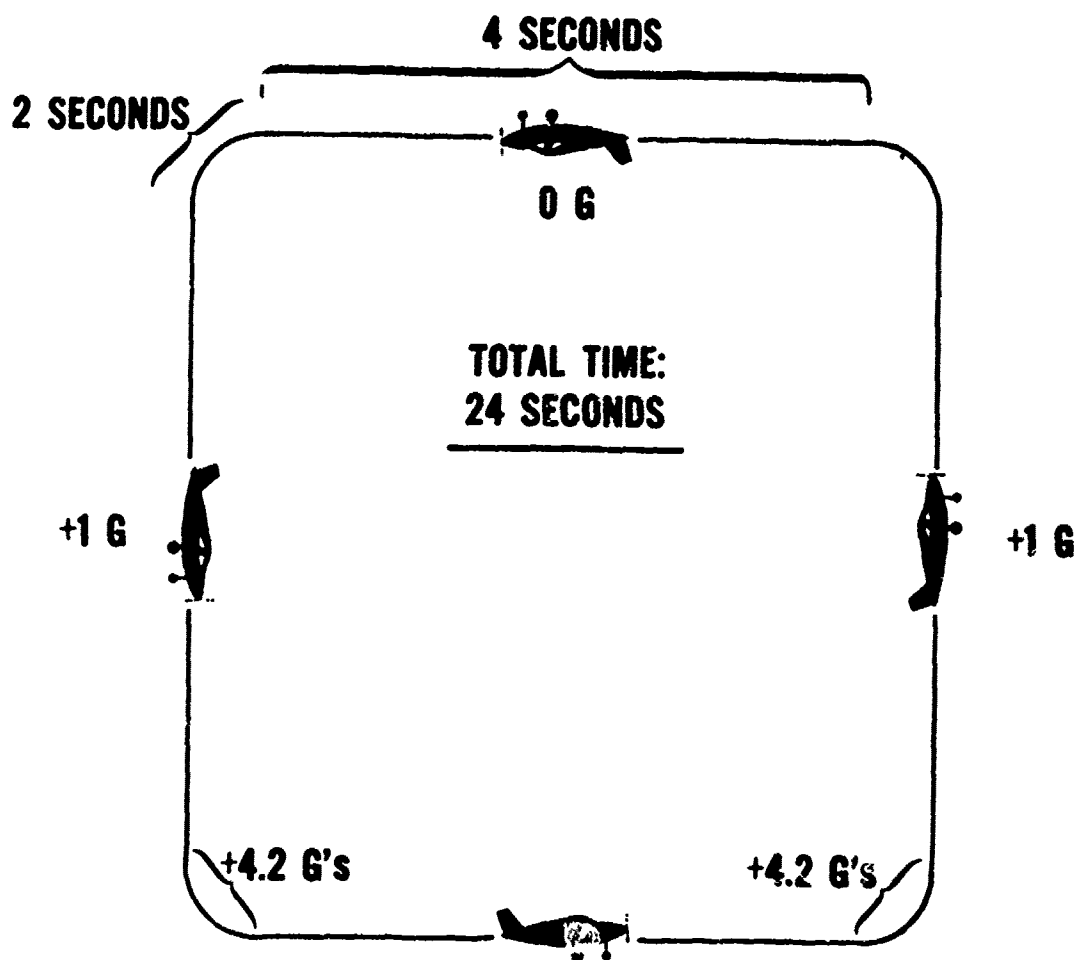


FIGURE 9.—Spins consume a great deal of altitude in a relatively short period. Therefore, start these at a safe altitude.

creases resulting in the stretching of their walls. "Stretch receptors" in the aortic arch and carotid artery detect the extent of this stretch and send nerve signals through the "visceral" nervous system into the central nervous system where the signals are processed in the lower brain and result in outflow signals that are carried by the parasympathetic nervous system (in this case, the vagus nerve portion) to the heart. The impulse is inhibitory and the heart rate slows. The blood pressure then tends to lower toward "normal".¹

The above reflex arc represents a "feed back" mechanism and is a "cybernetic" governor in the complete sense on the term. In addition to the adjustment which keeps the arterial pressure from rising excessively there is a parallel balancing mechanism which comes into play if the mean blood pressure is too slow. This causes a reflex nerve arc to send impulses through the

sympathetic nervous system to the heart resulting in a faster rate and an increase in blood pressure. The reciprocal relation between blood pressure and heart rate as controlled by the above two reflexes is known as "Marey's Law". These reflex adjustments require about five seconds to come into play. Therefore, if one experiences a rate of onset of one G per second, it is obvious that unless some other interim method is used to compensate, a force generated by five G's can be reached before physiologic reflex compensation results. In the positive G_z direction, blackout occurs unless some other compensation mechanism is used. (Other compensation methods include holding the breath and forcefully exhaling and, or, leaning forward to decrease the distance of the column of blood between the heart tip and the eye level (base of the brain))^{1,2}.



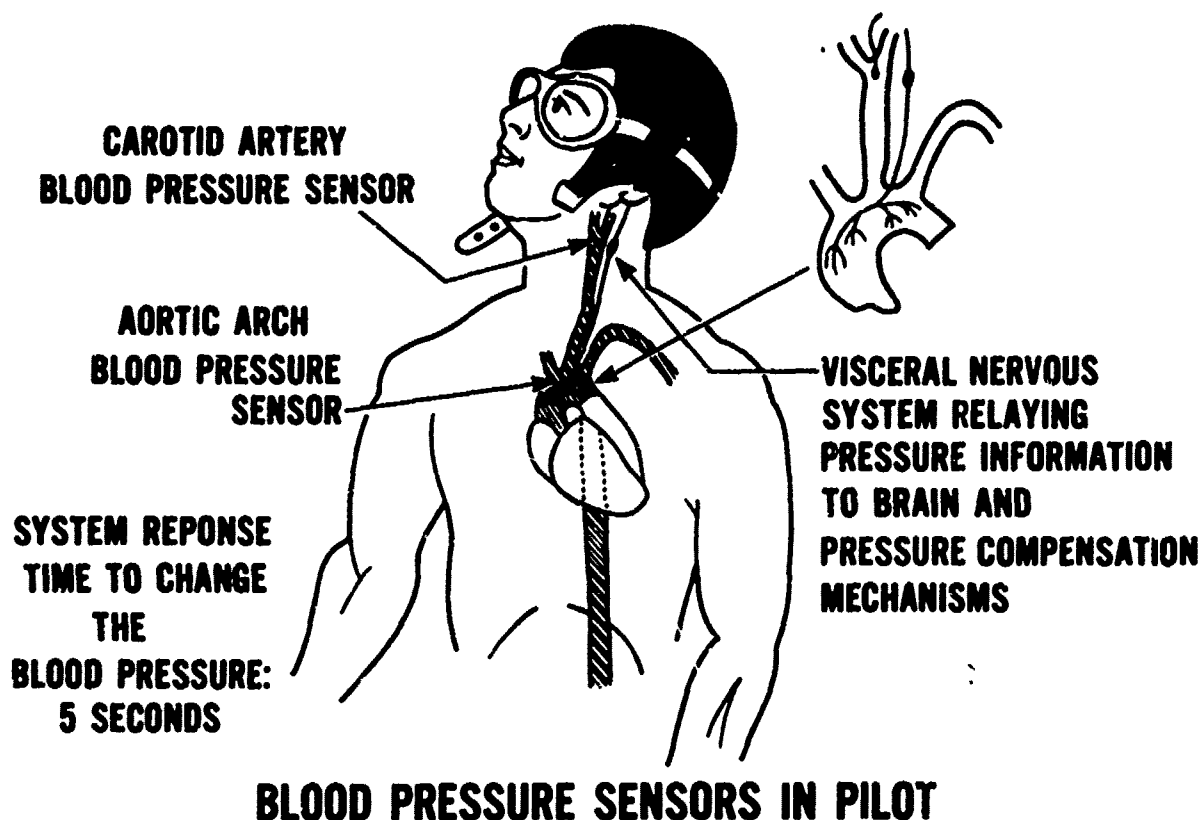
INSIDE SQUARE LOOP

FIGURE 10.—The square loop requires a high level of G's on entry and recovery.

In addition to the stretch "pressure sensors" (also called baroreceptors or pressoreceptors) described above, there are certain additional regulator mechanisms including the closing or opening of the tiny arteries just before the capillary network. The vast numbers of these tiny arteries (arterioles), their sensitivity to nerve stimulation, and their critical point of location in the arterial system, make them powerful additional controllers of blood pressure. Also, adrenalin release into the blood in highly stressful (+) G_z circumstances can raise blood pressure through its cardiac stimulation effect. In very stressful (-) G_z maneuvers, this should have an adverse effect by forcing the heart to send blood to an already overengorged brain.

Figure 12 shows in the center top, a simplified schematic diagram of the one (+) G_z "normal" situation, illustrating the tip-of-the-heart to eye level distance, the position of the liver between the diaphragm and the heart, and the relative size of the aorta and major outflow arteries. Large veins (jugulars) return the blood from the head to the heart and a large vein (the vena cava) runs parallel with the aorta and returns blood from the lower limbs and trunk to the heart.

At the right is shown a four (+) G_z force which results in a pulling away of blood from the vessels supplying the brain. The heart is smaller because it cannot fill well since the lower trunk and leg vessels now have pooled blood.



BLOOD PRESSURE SENSORS IN PILOT

FIGURE 11.—Aerobatic pilots should be familiar with the physiologic mechanisms which compensate for G force imposition during aerobatics.

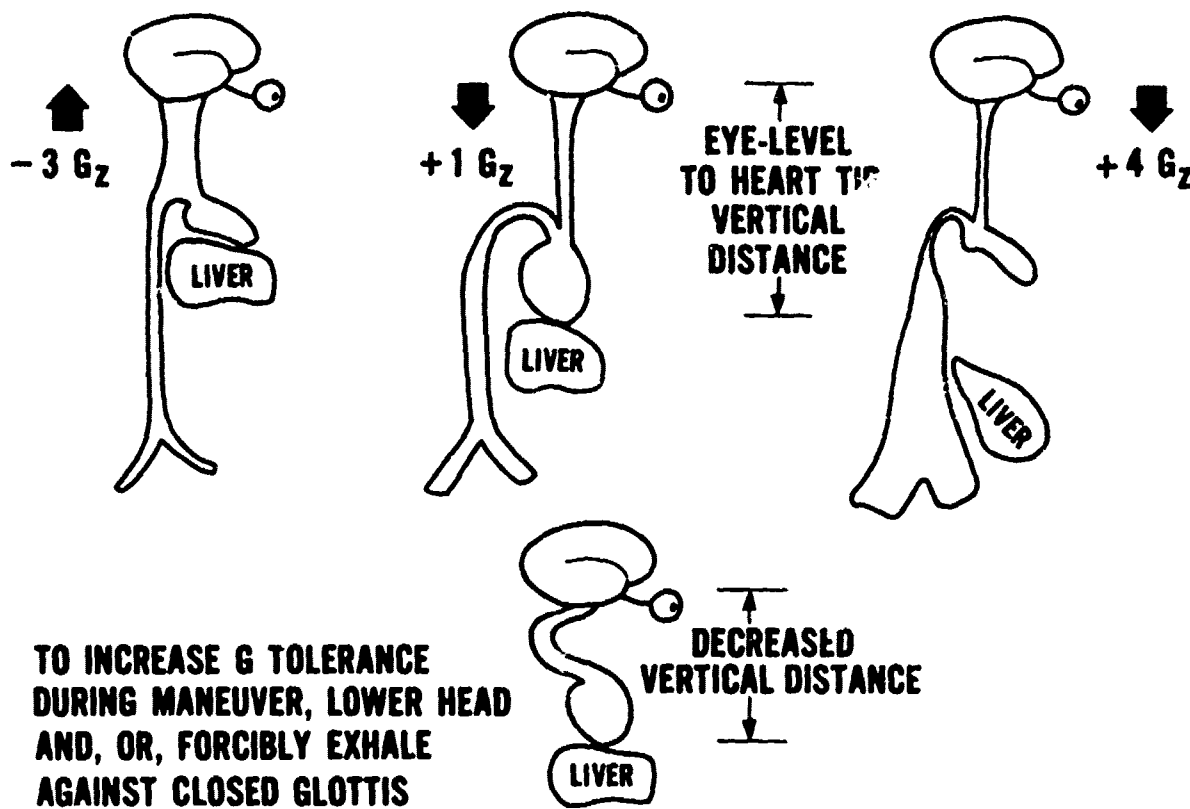
The veins especially dilate because of their thin walls relative to arterial walls, and considerable blood pools in the abdominal "splanchnic" veins. The liver has slid toward the pelvis. Gray-out to unconsciousness may occur in the experienced aerobatic pilot because of decreased blood flow through the brain and eye retina if a four (+) G_z acceleration is experienced steadily for one minute.

At the left, a three (-) G_z force is shown. The blood in the major arteries and veins to the head is forced toward the head and the brain and eyes are engorged. The experienced pilot feels head discomfort, fullness sensations and some have reported that the lower lid creeping over the cornea gives a "reddish" visual sensation. The whites of the eyes become bloodshot and at higher (-) G_z forces, tiny capillaries may rupture (due to high arterial pressure and high venous pressure, these on both ends of the thin walled capillaries) giving small red hemorrhages. Some persons have experienced

retinal capillary hemorrhages, also, resulting in several days of "spots before the eyes". Note that the liver has pressed up through the diaphragm against the heart and lungs, making breathing difficult. Note also that the aorta to the lower trunk and legs is low on blood volume. There is no effective way to compensate for the above (-) G_z changes as there is for the (+) G_z changes. Unconsciousness may occur if 4.5 (-) G_z is imposed for five seconds, but, as with (+) G_z unconsciousness, as soon as the accelerative force is removed, a rapid return to consciousness occurs with restoration of circulation (due to the highly oxygenated status of the arterial blood—assuming the pilot is not exposed to a hypoxic environment).

The lower center diagram of Figure 12 illustrates that if the vertical distance between the heart and the brain is decreased, and, or, the thoracic and abdominal pressures are increased prior to, or during, a (+) G_z acceleration by attempting to exhale against a closed glottis

CIRCULATION DYNAMICS DURING G_z ACCELERATION



**TO INCREASE G TOLERANCE
DURING MANEUVER, LOWER HEAD
AND, OR, FORCIBLY EXHALE
AGAINST CLOSED GLOTTIS**

FIGURE 12.—The human body is a relatively soft and flexible structure, hence the specific effects of vertical axis accelerations upon it.

(valsalva maneuver), an increase of (+) G_z tolerance can be obtained of an additional 1 to 2 (+) G 's.¹⁵

Figure 13 illustrates the vertical "8", a maneuver that when entered from the inverted position and performed well in competitive aerobatics is good for 40 points (Aresti system).¹⁶ If the upper loop is "inside" and the lower "outside", 36 points are possible. The maneuver in Figure 13 combines high aerodynamic performance requirements with pilot physiologic limits. The figure is shown in the "Aresti" system of "aerocryptographic" portrayal, with the broken lines indicating (–) G_z forces. The competitive aircraft with inverted fuel systems, favorable power/weight ratios, and fairly light wing loadings are particularly suited for this maneuver. Examples are the Moravan National Corporation Zlin 526A or 526AS (160 hp), the DeHavilland DHC-1B-2-S3 Chipmunk (200 hp) and the Yakovlev YAK-18PM (300 hp). The Pitts

Aviation Enterprises Pitts S-1 Special also performs the maneuver well.

In communication with various pilots who have practiced the maneuver, periods of unconsciousness occur at the 7–9 o'clock position on the inside loop which follows the outside loop.¹⁷ If the inside loop is performed first, followed by an outside lower loop, the unconsciousness does not happen, but, as previously stated, the maneuver is then worth fewer points.

The mechanism of unconsciousness experienced in the maneuver as portrayed in Figure 13 is as follows. The maneuver is entered from the inverted position which has already resulted in a certain congestion of the brain and eyes with blood since there will be a one (–) G_z force. The pressure receptors in the aortic arch and carotid arteries (Figure 11) will have sensed the blood engorgement and will have sent signals to slow the heart. In addition, the large veins of the neck will be stretched by the slowing of

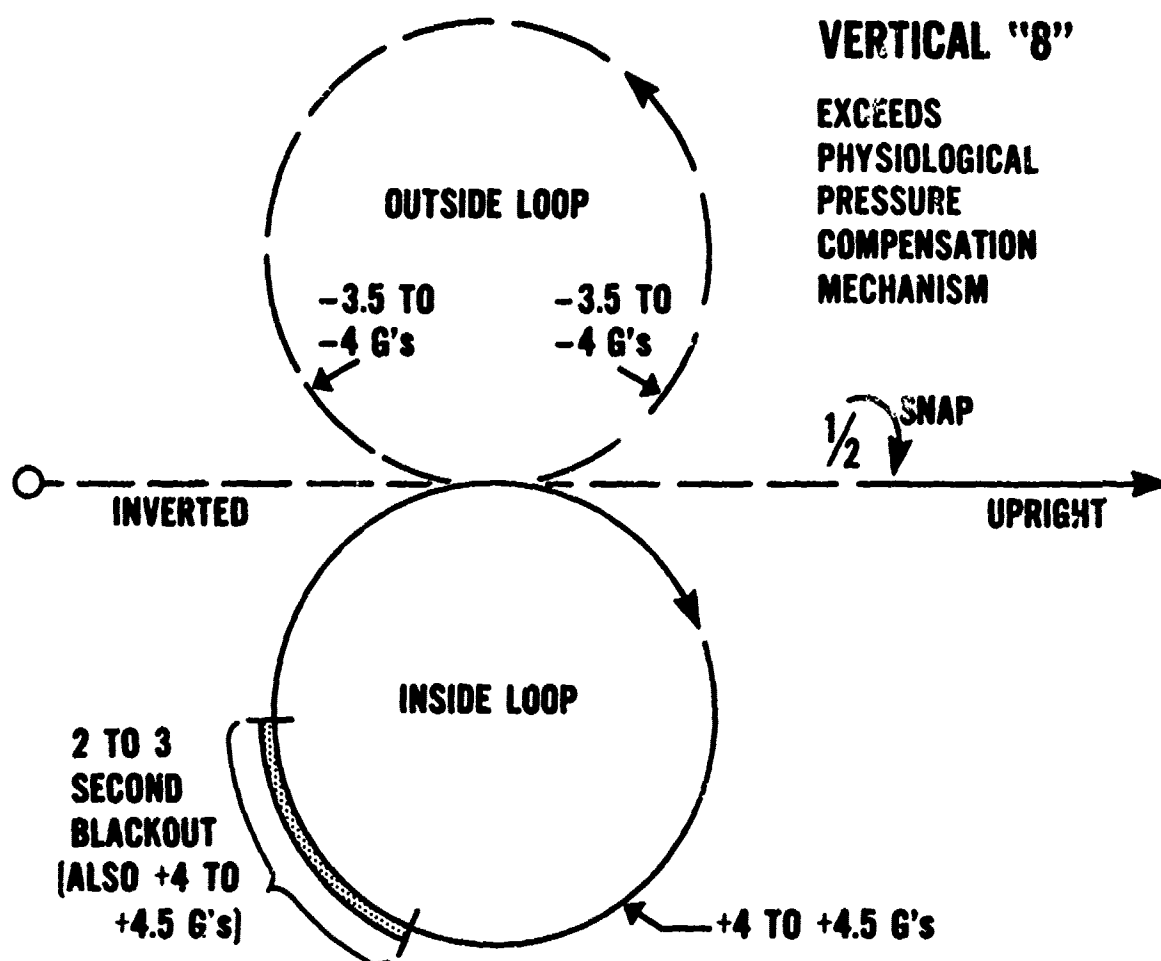


FIGURE 13.—This maneuver is very stressful from the physiologic as well as the aerodynamic standpoints.

the venous blood due to the $(-)$ G_z force tending to retard the return of the blood from the head to the heart. Normally the venous blood returns to the heart in a gravity-feed system. In the $(-)$ G_z position, this venous return is, therefore, somewhat impaired. There is a reflex stretch mechanism in these great neck veins which is designed to speed up the heart and cause it to pump more blood in the presence of venous overload (this is known as the "Bainbridge" reflex). Stretch receptors in the great neck veins detect excessive venous blood pressure and send signals through the visceral nervous system to the central nervous system, with return signals through the sympathetic nervous system to stimulate the heart. This reflex is designed for the $(+)$ G_z circumstance, and has an adverse effect in a $(-)$ G_z maneuver since it results in the heart attempting to pump more blood into an

already overloaded head circulation having decreased venous outflow. Because of the engorged slow-flowing blood circulation, the brain becomes somewhat hypoxic since it extracts much of the oxygen from the slow moving blood during the outside maneuver at the 4-5 o'clock and 7-8 o'clock positions.

Following the completion of the outside loop which required at the 7-8 o'clock position 3.5 to 4 $(-)$ G 's along the G_z axis to round-out horizontally, the inside loop is abruptly begun. Here the $(+)$ G 's begin to be imposed on the G_z axis, an imposition for which the blood pressure physiology is not attuned. On the contrary, all reflexes have been working against the $(-)$ G_z axis. There is a five second delay in reflex response from one $(+)$ G_z to increased $(+)$ G loadings, and when the loadings begin from the $(-)$ G_z side, this response is increased by several

seconds. When the first strong (+) G_z forces hit at the 4-5 o'clock position, the nervous mechanisms are still trying to catch up with the imposed (+) loading and all of the compensations have to be made in the completely opposite direction. These are possibly aided by the valsalva maneuver and by head lowering. The blood flow slows to the brain and at the 6 o'clock position the brain has extracted much of the oxygen. Some slight increase in circulation may be gained at about the 6 o'clock point as the G forces reduce somewhat. However, the acceleration against the pull of gravity at the 7-8 o'clock position imposes 4-4.5 (+) G 's upon an already overstressed, barely compensating, cardiovascular system. This new load decreases the circulation once again and, this time, loss of consciousness occurs at the 7 o'clock-9 o'clock position. Since the large G forces begin easing off after the 8 o'clock position, and the physiological pressure maintenance reflexes begin to have an effect, circulation to the brain is reestablished and consciousness returns.

Physiologically, no permanent harm occurs to the healthy individual in the above maneuver. World War II dive bomber pilots found that if they did a (-) G push over they were more likely to black-out when the (+) G recovery was made than was so if they rolled over and made a (+) G entry to the dive. In view of their loss of consciousness during the pull-up when the aircraft itself was under great aerodynamic stress, they feared inadvertent control movements which might structurally damage the aircraft under these conditions having the visual loss of reference "black-out", prior to, and just after, the unconsciousness. Also, the relaxed hold on the stick while unconscious could lead to a dive into the ground. Accordingly, they trimmed for a predetermined amount of nose up flight prior to the point of possible loss of consciousness. The aircraft, thus, tending to do the proper thing while the pilot was an "inert passenger".

Physiologic Tolerance

It appears desirable that, depending upon the pilot and aircraft, no maneuver be routinely performed which leads to unconsciousness at any point. Physiologically, humans progressively

adapt within limits to imposed strains and stresses, and with practice, any maneuver will have less and less of an effect (again, within limits, depending upon human physiology and the individual pilot). A lay off of some days or weeks can result in a lowered G tolerance, but, normally, this returns rapidly with practice. One old-time (1930's) aerobatic pilot (known as the "batman") fixed a harness in his garage and hung upside down for a few minutes each day. This would give a one (-) G_z acceleration and, possibly, he did maintain a slight increased physiologic tolerance in the (-) G_z axis. However, (-) G_z adaptation does not increase as effectively as is the case with (+) G_z adaptation, since, as already mentioned, the physiologic mechanisms are designed to counteract (+) G_z accelerations.

Other factors which affect G tolerance are (1) the skeletal anatomy, (2) the cardiovascular architecture, (3) the nervous system, (4) the quality of the blood, (5) the general physical state and (6) experience and recency.

Short, squat individuals would inherently have an edge toward G tolerance maximum levels over tall long-bodied, long-necked, individuals, although superb aerobatic pilots are, of course, found in the latter category. A highly efficient heart, free of coronary disease, and capable of raising the blood pressure rapidly, upon demand, is a prerequisite to safe, prolonged aerobatics. Some very young individuals have such elastic arteries that attempts to raise blood pressure are partially thwarted by lateral distension of the vessel walls. Normal aging results in a decrease in elasticity in arterial walls and, in this respect, acts to increase the tolerance to (+) G_z accelerations. The nervous system involves temperament (some persons will never emotionally adapt to aerobatics because of fears instilled in childhood or because of an inability to see the point of such activity). The quality of the blood relates primarily to its hemoglobin content (this is oxygen carrying component and should be between about 13-17 grams %—females should be especially wary of iron deficiency anemia), its salt content (be sure to have adequate $Na^+ Cl^-$ in hot weather) and water content (excessive dehydration lowers blood volume and the ability to change blood pressure).

The general physical state includes adequate sleep (at least seven hours prior to aerobatics), absence of infections (never conduct aerobatics with an illness—viral or bacterial), absence of hangover or drug effects (never undertake aerobatics with a hangover or while taking alcohol or any drug) and good physical fitness. Aerobic pilots should not become obese, "out-of-shape", or under "crash diets". Experience leads to knowledge and understanding and the development of additional tolerance to G forces (1-2 G's). Recency leads to physiologic adaptation and fitness and an increase of perhaps one to 1.5 additional G. This is lost in a week or so of layoff, but comes back rapidly after warm-up.

With respect to the physical and mental fitness of aerobic pilots, one female pilot during the mid-1960's had a severe anemia and lost consciousness in a maneuver while practicing for the international competition. The plane nosed over and dove into the ground with fatal consequences. Also, severe emotional upsets preceding competitive aerobatics can lead to excessively low maneuvers and crashes.¹¹ Documented loss of consciousness during (+) G_z G's in closed course air racing due to a weakened condition caused by diarrhea exists (pylon racers can pull 4-5 (+) G_z G's for several seconds).¹² In the same study, a pilot who suppressed information concerning an earlier heart attack, died during the stresses of the race. If at any time the pilot does not feel mentally or physically up to par, or if his aircraft, the environment, or the general circumstances, seem wrong, postponement or cancellation should be accomplished. A word of caution on alcohol: no alcohol for 24 hours prior to aerobatics, to avoid the hangover effect, and, once again, never perform with a hangover. Do the celebrating after the performance!

One additional point of caution. Use only aircraft designed for aerobatics in conducting these maneuvers (unless the pilot is a highly skilled test pilot who knows the limits of the aircraft and performs for demonstration purposes). Always wear a parachute during aerobatic maneuvers and plan ahead concerning escape from maneuver points of possible structural failure. In inverted flight with (-) G_z loadings, a double seat belt is a good idea, as is a shoulder harness. Never leave loose cushions

or other objects in the aircraft which can jar loose and jam the controls. The above and related points were also stressed by Duane Cole on 4 August 1972 at the International Aerobatic Club Meeting, Experimental Aircraft Association 20th Annual Convention, Oshkosh, Wisconsin. With respect to the duration of aerobatic routines, the late Bevo Howard used 12 maneuvers during performances in his Buecker Jungmeister. These included a series of slow rolls in a 360° circle, a hammerhead stall and turn, an 8-point sectional roll, a 1½ snap roll, an inverted snap, a double snap, a double snap on top of a loop, a square loop, a vertical 8 (inside loop to outside loop), a vertical snap, a spin, inverted flight with hands off the controls and an inverted ribbon pickup. The above maneuvers required approximately 15 minutes and obviously would be quite fatiguing at the end. Howard kept in good physical condition by swimming.

At the 26 May — 4 June 1972 "TRANSPO" at Washington, D.C.'s Dulles International Airport, the following times were clocked for aerobatics by the indicated pilots or groups:

Scotty McCray (Glider)	7 minutes
Bob Hoover (Shrike)	10 minutes
Mary Gaffaney (Pitts)	10 minutes
T. Poberezny, C. Hillard, G. Soucy (Pitts—formation)	15 minutes
Walt and Sandi Pierce (Dual aerobatics)	10 minutes
Hughes and Kalzian (Wing riding) ..	10 minutes
Dawson Ransome (Pitts)	10 minutes
Bob Hoover (F-51)	15 minutes
Art Scholl (Chipmunk)	10 minutes

Average: 10.8 minutes

It is apparent from the above that by historical precedent and present practice, the average series of aerobatics covers about 11 minutes. Eleven minutes of consecutive aerobatics is quite fatiguing and illustrates the necessity for maintaining good physical conditioning and health.

Figure 14 shows the maximum limits of human tolerance to G's as determined in large centrifuges.¹³ Note that for (+) G_z, the point where grayout begins for the uninitiated is three G for five seconds. Eight (+) G_z for 15 seconds causes blackout and temporary unconsciousness, even in the most experienced individual. A military G-suit (sometimes referred to as 'ne

"Anti-G" suit) can provide a tolerance of 4.5 (+) G's in the Z axis for five minutes.*

The (-) G_z tolerance for students is two to five seconds and causes subjective discomfort (as noted earlier, two (-) G's is a net change of three G's from one (+) G_z). The experienced pilot can tolerance 4.5 (-) G_z G's for five seconds before head pain (headache—referred to as cephalalgia), breathing discomfort (the lungs are pressed by the liver) and other subjective unpleasant sensations lead the pilot to terminate the maneuver. Note that the (-) G's cause enough discomfort to lead the pilot to terminate the negative maneuver prior to loss of consciousness. In this sense, outside maneuvers are physiology safer than inside maneuvers. In fact, the first pilot to ever perform a loop, Adolphe Pegoud at France, in the summer of 1913 performed both outside and inside loops.^{3 15} He repeatedly and routinely demonstrated outside loops (flying "over the top", down-under, and back up) in a Bleriot monoplane. The airplane,

* During World War Two, German Stuka dive bomber pilots were able to adapt to 8 (+) G's for a few seconds on pull out by a combination of the Valsalva maneuver and bending over to a rather extreme angle (personal communication, Dr. Harald von Beekh, former Stuka pilot).

which used wing warping for bank, was modified by adding stronger "landing wires" for (-) G to the wings and a heavier horizontal tail. The outside loop, as noted, was entered from a dive with the aircraft pushed forward over on its back and allowed to curve up and around to the starting point. Pegoud also performed two other types of (-) G_z maneuvers and tail slides.

For vertical eight and other maneuvers that lead to unconsciousness, the pilot should discontinue these at the point where visual sensation begins to change. Consideration should be given to logging the periods and points of unconsciousness in various extreme maneuvers in order that long range corrective action can be taken in terms of modifying the repertoire.

Figure 15 lists the G_z tolerances in the (+) and (-) directions of the average healthy experienced human. Note that the one (+) G_z axis tolerance is about 20 hours in the immobile sitting position, and that after this period, the desire to slouch, to drop the head to one side or the other, or to lean on a table, not to mention to lie down, becomes overwhelming. All of these changes lead to diminishing the height of the blood column from the heart to the brain. After two hours of standing straight with no move-

HUMAN ACCELERATION TOLERANCE LIMITS

TYPE OF G	DIRECTION OF BODY MOVEMENT	AIRCRAFT MANEUVER	ONSET OF INITIAL SYMPTOMS	EXPERIMENTAL HUMAN MAXIMUM EXPOSURES	PHYSIOLOGICAL LIMITS
+	HEAD TO FOOT	PULL OUT OF DIVE OR TIGHT LEVEL TURN	STUDENT: 3G 5 SECONDS GRAYOUT	8G FOR 15 SECONDS (4.5G FOR 5 MINUTES WITH G SUIT)	BLACKOUT TO UNCONSCIOUSNESS
-	FOOT TO HEAD	PUSHOVER	STUDENT: 2G 5 SECOND SUBJECTIVE DISCOMFORT	4.5 G FOR 5 SECONDS	PAIN (HEADACHE)

FIGURE 14.—This chart is for application to aerobatic students.

ACCELERATION TOLERANCES (EXPERIENCED INDIVIDUALS)

G	TIME	SYMPTOM
+8	15 SECONDS	BLACK-OUT TO UNCONSCIOUSNESS
+7	15 SECONDS	BLACK-OUT TO UNCONSCIOUSNESS
+6	20 SECONDS	BLACK-OUT TO UNCONSCIOUSNESS
+5	30 SECONDS	BLACK-OUT TO UNCONSCIOUSNESS
+4	1 MINUTE	GRAY-OUT TO UNCONSCIOUSNESS
+3	3 MINUTES	GRAY-OUT TO UNCONSCIOUSNESS
+2	13 MINUTES	GRAY-OUT TO UNCONSCIOUSNESS
+1	20 HOURS (SITTING)	2 HOURS-STANDING, NO MOVEMENT
0	21 DAYS (MAXIMUM EXPOSURE TO DATE)	
-1	10 MINUTES	SUBJECTIVE DISCOMFORT TO UNCONSCIOUSNESS
-2	1 MINUTE	SUBJECTIVE DISCOMFORT TO UNCONSCIOUSNESS
-3	30 SECONDS	RESPIRATORY DISTRESS ADDED TO UNCONSCIOUSNESS
-4	6 SECONDS	PAIN (HEADACHE) ADDED TO UNCONSCIOUSNESS
-5	4 SECONDS	PAIN (HEADACHE) ADDED TO UNCONSCIOUSNESS

FIGURE 15.—This table represents a spectrum of G limitations for the average experienced aerobatic pilot.

ment (as soldiers at attention), Marey's Law and its backup, the Bainbridge reflex, begin to fail, and the subject will faint unless he can move around (reestablishing blood circulation—partly through the leg and arm muscles squeezing the veins, the latter provided with one-way valves directing the pooled blood toward the heart), sit or lie down.

Figure 15 contains data on the upper tolerances of fit, experienced, aerobatic pilots, with unconsciousness as the ultimate end point. Centrifuge studies by the U.S. Navy, Johnsville, Pennsylvania, facility, reveal the somewhat lower tolerance for adult male research subjects when "grayout"; the loss of peripheral vision, is the end point for (+) G_z and throbbing headache for (-) G_z (personal communication, Dr. Harold von Beckh). These are as follows:

Time	(+) G_z	(-) G_z
3 seconds	12.0	4.0
10 seconds	4.2	3.8
15 seconds	3.6	3.2
20 seconds	3.4	2.5

The (+) G_z tolerance is so high for three seconds because the brain can operate on the oxygen diffused in its tissues for this brief period. The 4.0 (-) G_z tolerance represents a net change of five G's from the one (+) G_z point (as compared with three G's to the four (+) G_z point).

Incidentally, one reason we lie down to get the most restful sleep is that we place the G_z axis parallel with the pull of gravity, thus minimizing the work requirements to raise the blood against the field of gravity. By periodically turning during sleep around the G_z axis, the

gravitational pull in the less significant G_x and G_y axes is also averaged out during the sleep.

Some four-legged animals can sleep in the standing position, but note that their G_z axis is parallel with the horizontal and they keep the head approximately at heart level. Also, some cranes sleep on one locked leg, and here too the head is tucked near the horizontally held body at heart level. Animals that hang upside down have special adaptative structures to control the blood flow in the $(-)$ G_z position.

Concluding Comments

Aerobatics for the experienced pilot is the true elixir of flight. Too many pilots, however, have been lost through inadequate knowledge of the physiology of aerobatic flight. All desiring to practice this advanced form of flight should assimilate basic knowledge of the physiologic aspects of aerobatic flight.

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